Sedimentary Geology 282 (2012) 124–141

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Deposition by the 2011 Tohoku-oki tsunami on coastal lowland controlled by beach ridges near Sendai, Japan

Yasuhiro Takashimizu [a,*], Atsushi Urabe [b], Koji Suzuki [b], Yoshiki Sato [c]

[a] Faculty of Education, Niigata University, Niigata, 950-2181, Japan
[b] Research Institute for Natural Hazards and Disaster Recovery, Niigata University, Niigata, 950-2181, Japan
[c] JSPS Research Fellow, Graduate School of Science, Kyushu University, Fukuoka, 812-8581, Japan

ARTICLE INFO

Article history:
Received 10 November 2011
Received in revised form 4 July 2012
Accepted 9 July 2012
Available online 20 July 2012

Keywords:
2011 Tohoku-oki tsunami
Tsunami deposits
Sedimentary facies
Grain size
Grain fabric
Diatom analysis

ABSTRACT

A study of the 2011 Tohoku-oki tsunami deposits on the coastal lowland of the Sendai Plain, Japan was carried out along a shore-perpendicular survey line in the Arahama area. Field descriptions and tsunami water depth measurements were complemented by sedimentary analyses, including grain size, grain fabric and diatom analysis. The tsunami deposits show a generally fining-inland trend along the 3.4 km long transect. The depositional facies, grain size analysis and grain fabric data suggest that most of the tsunami deposits were laid down during the tsunami inflow, except at one site. These tsunami deposits are characterized by parallel-laminated or massive sand and silt with pieces of woods, fragments of glass, rip-up mud clasts and an erosional base. Minor backwash deposits overlying the inflow sand layer were only observed on one beach ridge and attributed to the topographic high. Marine diatom species comprised only approximately 2% of the diatom assemblage in tsunami deposits and their content decreased landward. In this study, diatom assemblages were similar in the rice field soil and tsunami layers, suggesting that the muddy fraction of the deposits mainly consists of sediments derived from the tsunami-eroded rice field soil. As a result of soil erosion, the tsunami had a high suspended sediment load. Furthermore, after the first tsunami inundation, seawater left by the tsunami did not drain completely to the sea because of the high coastal beach ridge and/or coastal subsidence due to the massive earthquake. Therefore, strong tsunami outflows to the sea did not occur and these areas were covered by mud deposited from stagnant water.

1. Introduction

The 2011 off the Pacific coast of Tōhoku Earthquake (Mw 9.0) that occurred on 11 March 2011 generated a large tsunami that inundated several kilometers inland (Figs. 1 and 2). This tsunami hit broad coastal areas of the eastern coast of Honshu island of Japan and nearly 19,000 people died or went missing as a result. Land subsidence of several tens of centimeters observed in the coastal lowland of the Tōhoku area is attributed to tectonic movement related to the earthquake, with a maximum vertical displacement of 1.2 m recorded at the GPS-based control station Oshika, Ishinomaki city, Miyagi prefecture, eastern Japan (Geospatial Information Authority of Japan, 2011).

There are many sedimentological studies of recent, historic and pre-historic tsunami deposits on coastal lowlands (e.g. Nanayama et al., 2003, Moore et al., 2006; Hawkes et al., 2007; Hori et al., 2007; Moore et al., 2007; Paris et al., 2007; Takashimizu et al., 2007; Choowong et al., 2008; Fujino et al., 2008; Goto et al., 2008; Morton et al., 2008; Nanayama, 2008, Nishimura, 2008; Matsumoto et al., 2010; Chagué-Goff et al., 2011). There are also studies that report on paleo-current directions based on the sedimentary features of tsunami deposits on coastal lowland, although not as many (e.g. Nanayama, 2008; Naruse et al., 2010; Wassmer et al., 2010). The reason for this is that identifying cross-laminae in tsunami deposits on coastal lowland is difficult. Indeed, most tsunami inflow deposits are characterized by parallel laminations or massive structures. For example, Nanayama (2008) discussed the paleo-current directions of the 1993 Hokkaido-Nansei-oki earthquake tsunami based on cross-lamina measurements and Wassmer et al. (2010) also reconstructed those, using anisotropy of magnetic susceptibility. Their attempts are significant from the viewpoint of the reconstruction of paleo-tsunami behavior on coastal lowland.

Studies of diatom assemblages in tsunami deposits, characterized by the presence of brackish and marine diatoms, are also important for paleo-tsunami science, because the diatom assemblage of tsunami deposits is one of the tools used to determine their origin (e.g. Dawson et al., 1996; Dawson and Smith, 2000; Chagué-Goff et al., 2002; Sawai, 2002; Dawson, 2007; Takashimizu et al., 2007; Sawai et al., 2009).

The purpose of this paper is to present the sedimentary features of the 2011 Tohoku-oki tsunami deposit on a coastal lowland with beach

* Corresponding author. Fax: +81 25 262 7158.
E-mail address: takashimi@ed.niigata-u.ac.jp (Y. Takashimizu).

0037-0738/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.sedgeo.2012.07.004

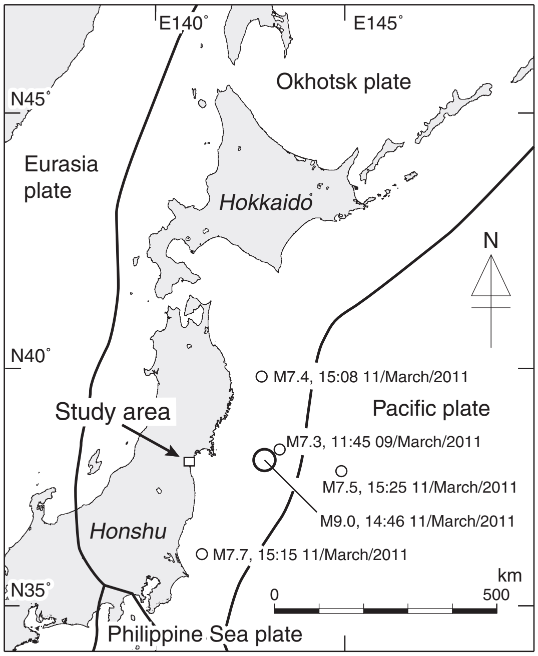

Fig. 1. Study area and epicenter of the main shock and aftershocks of the 2011 Tōhoku earthquake. Plate boundary data derived from Wei and Seno (1998). Data related to the epicenter of the main shock and aftershocks are from the Japan Meteological Agency (2011).

ridges and to compare some relationships among these features, distance from the coast and tsunami water depth. Finally, we attempted to reconstruct the behavior of tsunami flows caused by the 2011 event. Bed thickness, grain size, grain fabric and diatom assemblages are discussed in detail. These data can supply basic information about the 2011 Tohoku-oki tsunami and contribute to the identification of ancient tsunamis in sedimentary sequences.

2. Study area

The study area is located in the northern part of the Sendai Plain, Miyagi prefecture, eastern Japan. The northern Sendai Plain has three beach ridges at heights of around three meters (Matsumoto, 1984), which are the landward BR I (5000–4500 y. B.P.), the central BRII (2000–1700 y. B.P.) and the seaward BR III (700 y. B.P.–present day). The survey line for the present study was set in the Arahama area from a site 0.6 km inland to a site 4.0 km inland (Fig. 2). Inter-ridge lowlands have been used as agricultural fields (rice fields), and windbreak forests and houses are distributed on the ridges (beach ridges II and III). However, BR I in the study area is used by the Sendai-Tobu expressway and reaches approximately 6 to 9 m in height above the ground.

Four historic and pre-historic tsunami deposits were also reported from the study area (Sawai et al., 2008). The latest and best-studied is the 869 Jogan tsunami deposit (Abe et al., 1990; Minoura and Nakaya, 1991; Minoura et al., 2001; Sawai et al., 2008; Sugawara et al., 2011) which is found up to approximately 2.7–2.8 km inland from the paleo coastline (Sugawara et al., 2011).

3. Methods

The current directions were inferred from the orientation of drift wood, plant rods, wood or glass debris with elongated shape, and drag or scour grooves caused by the tsunami at each survey site. Lithological and sedimentological features were described at each site and 15 oriented undisturbed samples were taken from the ground surface along a survey line at approximately 200 m intervals (Fig. 2). The tsunami water depths were also measured from water marks on the outward walls of houses and buildings, floated debris caught in trees, and scratches caused by floated/drifted debris, and are based on 190 measurement points. Water depth measurements were taken in an area of the Sendai plain between the Nanakita-gawa and Natori-gawa Rivers on the 11 and 12 May 2011 (Fig. 2). In this paper, we use the tsunami "water depth" for the "maximum water depth" at each measurement point. The thickness of tsunami deposit is also represented by the maximum measured thickness at each site. After the field survey, grain size analysis, grain fabric measurements and diatom analysis were carried out in the laboratory. Each sample was split into two subsamples for imbrication measurements and other analyses (e.g. grain size measurement and diatom analysis). Grain size distributions of recent foreshore, backshore and sand dune deposits and rice field soils were also analyzed to infer the origin of the tsunami deposits.

We used a settling tube grain size analyzer for the measurements of size distribution (Tamura and Nakayama, 1993; Naruse, 2005). The settling distance of the equipment was 150 cm, and the total measurement time was around an hour and a half to two hours depending on the water temperature. The measurement range of grain size was −1.0 to 6.0 phi with 0.2 phi intervals. The cumulative sediment weight was automatically logged, using an electronic balance that can measure a minimum of 1×10^{-4} g. Five sudden spikes were recognized in grain size distributions at sites 1, 10, and 15. We however omitted these spikes from the descriptions and interpretations, because they were interpreted as measurement errors (e.g. vibrations, generated air bubbles and others).

Grain size characteristics were analyzed using the classical method (moment method: Friedman and Sanders, 1978; Friedman and Johnson, 1982; McManus, 1988; Friedman et al., 1992) and a new procedure (normalizing: Endo and Masuda, 1996; Endo et al., 1996; Masuda and Endo, 1996). Grain size measurements were carried out in 1 cm intervals at each site. Recent beach ridge deposits (foreshore, backshore and sand dune sediments) on the Arahama coast were also measured using the same method. The average grain size (mean and median) and sorting (standard deviation) of each sample (in 1 cm intervals) of the tsunami deposit at each site were used to calculate a mean value for that site. We then calculated the "total grain size" distribution of the tsunami deposits along the survey line in order to obtain the "normalized grain size" distributions, which is the distribution obtained by dividing the sum distribution by the total number from all samples. We used a weighted coefficient for each grain size distribution assuming that the distance intervals between each site were the same, because the sampling sites are not equally distributed. The normalizing procedure consists of dividing the weight percentage in each phi class by weight percentage in the same phi class in the "total grain size" distribution. In the distribution pattern of the normalized grain size data, the coarse skewed shape shows that the coarse-grained particle fraction dominates the "total grain size", on the other hand, the fine skewed one indicates that fine-sized grains are dominant. The reason for using normalized data is that even if weight percentages at each site are low, the variation along the survey line is enhanced and easy to understand. Therefore the normalizing method is quite useful to obtain lateral variations in the tsunami deposits.

To prepare thin-sections for fabric analysis, the oriented undisturbed tsunami deposit at site 3 (Fig. 2) was vertically split in half. One half was completely dried at room temperature in the laboratory and slowly impregnated with epoxy resin. The sample was then cut with a petrographic saw along a flow-parallel direction, as inferred from paleo-current measurements. Imbrication angles (inclination angle of individual grains) of the sand fraction of the tsunami deposit were measured in 1 cm intervals on a large-sized thin-section and automatically analyzed using the software package Image J released by NIH, USA.